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Disposition choices based on energy footprints instead of recovery quota

Applying Pareto frontiers to analyze effectiveness of extended producer responsibility

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Abstract – This paper addresses the impact of disposition choices on the energy use of closed-loop supply chains. In a life cycle perspective, energy used in the forward chain which is locked up in the product is recaptured in recovery. High quality recovery replaces virgin production and thereby saves energy. This so called substitution effect is often ignored. Governments worldwide implement Extended Producer Responsibility (EPR). Policies are based on recovery quota and not effective from an energy point of view. This in turn leads to unnecessary emissions of amongst others CO2. This research evaluates current EPR policies and presents six policy alternatives from an energy standpoint. The Pareto-frontier model used is generic and can be applied to other closed loops supply chains under EPR, exploiting the substitution effect. The measures modeled are applied to five WEEE cases. We discuss results, pros an cons of various alternatives and complementary measures that might be taken.

Key words: extended producer responsibility, disposition, energy perspective, substitution effect, government policies, Pareto efficiency

JEL-codes: Q28, K32, C61

1. Introduction

The management of **C**losed-**l**oop **s**upply **c**hains (CLSCs) involves the acquisition, reverse logistics, disposition, recovery and resale of returns (adapted from Guide and Van Wassenhove, 2001). There are many types of returns, varying from products to reusable items, and ranging from returns immediately after sales till the end of the life cycle. Legislators increasingly hold **O**riginal **E**quipment **M**anufacturers (OEMs) responsible for the take-back and recovery of end-of-life (EOL) items.

Extended **P**roducer **R**esponsibility (EPR) is defined as 'a policy approach in which producers accept significant responsibility, financial and/or physical, for the treatment or disposal of products' (OECD, 2001). EPR policies have two distinct features: the shifting of responsibility upstream to the producer and the provision of incentives for producers to include environmental considerations in the design of their products, resulting in a life cycle approach. Note that OEMs (or their formal replacements) are responsible for recovery, not for collection. Thierry et. al (1995) present six recovery options, namely direct reuse, repair, refurbishment, remanufacturing, harvesting and recycling. Disposal is usually combined with energy recovery. Table 1 summarizes these options.

The listing is not meant to be hierarchical. Braungart et al. (2007) challenge us to avoid down-cycling, and recovery in whatever option should be competitive with virgin production of components, materials and energy. In this vision energy recovery options should not be on the lowest spot by definition, but rather feasibility of options varies per case.

Table 1: Outline of recovery options (adapted from Thierry et. al 1995)

Options	***Operations***	***Resulting output***
direct reuse	check on damage and clean	as is, e.g. for refill
repair	restore product to working order, some component repaired or replaced	original product
refurbishing	inspect and upgrade critical modules, some modules repaired or replaced by upgrades	original product in upgraded version
remanufacturing	manufacture new products partly from old components	new product
harvesting	selective retrieval of components	some parts, modules reused, others scrapped
scrap	shred, sort, recycle and dispose of	materials and residual waste
disposal	incinerate and landfill	energy and fluff

Today, EPR is found worldwide, but it started in the European Union with amongst others directives on packaging, automotive and electronics. But also non EU member-states like Norway, the Baltics and Switzerland as well as Asian countries like South-Korea, Japan, and Taiwan are now adopting similar legislation. In the United States, so called product stewardship is becoming more accepted and mandatory recycling is in place in some states (Nnorom and Osibanjo, 2008, Ogushi and Kandlihar, 2007, Chung and Yoshida, 2006). Today, many global companies, such as DELL, are adopting EPR worldwide by offering free recycling services, even when not mandatory in the region at hand.

In this paper we focus on legislatively imposed EPR, targeting recovery quota to be achieved by industry. These quota define minimum rates of recovered weight, which includes component, material and substance reuse and to some extent energy recovery. The *disposition* decision is crucial as it determines the recovery option. It denotes all operations determining whether a given product is in fact re-usable and in which way, including energy recovery. Thus, disposition results in splitting the flow of used products according to distinct recovery (and disposal) options. It may encompass inspection, separation, disassembly, shredding, testing, sorting, and storage steps (adapted from Fleischmann et. al, 2000).

Table 2 gives some examples on EPR in the automotive, Waste of Electronics and Electromechanical Equipment (WEEE) and packaging industry. Korea thereby combines WEEE and automotive into one law, the others have different regulations per waste stream. As Table 2 shows, directives apply blunt recovery quota, imposing a strong constraint on the disposition decision. Moreover, there is a tendency to increase these quota over time, although studies suggest that too high recovery quota may lead to costly and environmentally unsound solutions (Van Wassenhove et al., 2004, Walther and Spengler, 2005, Quariguasi Frota Neto et. al 2008b, Krikke et.al, 2003). But there seems to be a 'the more the merrier' attitude amongst regulators, for example in the automotive industry which aims for 95% recycling in 2015 (le Blanc, 2006). As a result, EPR directives are primarily waste avoidance acts.

Table 2: Recovery quota 2008 (2015)

Stream	Options	EU	Japan	Korea
Packaging	Recovery	60-75 %		
	Recycling	55-70 %		
Automotive	Recovery	85% (95%)	30% (70%)	85% (95%)
	Reuse and recycling	80% (85%)		
WEEE	White goods recovery	80%	50%	85%
	Brown goods recovery	75%	55%	80%

Policy makers deny crucial mechanisms with respect to economics and environmental impact. The cradle-to-cradle paradigm contemplates a more balanced view with respect to environmental impact of (closed loop) supply chains. Particularly including *energy use* as an important variable is essential (Braungart, et. al, 2007). Energy use can be seen as the root cause of a number of emissions, amongst which CO2. Moreover, taking energy use from a 'closed loop' perspective implicitly enhances high quality recovery as we will motivate in this paper.

This paper contributes to the existing body of literature as it develops and uses a method to evaluate and analyze EPR policies from the energy angle. The method provides the optimal disposition of returns to recovery options in terms of economic benefits and energy consumption, given the constraints or incentives posed by the policies at hand. Contradictory to the literature, we not only evaluate current EPR policies but suggest alternatives policy approaches on a conceptual level.

We present a generic EPR based closed-loop supply chain model in Section 3. We parameterize the model for five different WEEE cases in Section 4 and discuss results. Section 5 draws conclusions and also elaborates on the wider implications of the work. Also, we suggest follow up research. But first in Section 2 we review the literature on applicable modeling, meaning eco-eco models for closed-loop supply chains under EPR, with a focus on disposition decisions.

2. Eco-eco impact and modeling of closed-loop supply chains

Since Al Gore's "Inconvenient Truth" it is difficult not to know about the greenhouse effect and its main cause: carbon dioxide. These emissions are largely related to increased energy use and important contributors are (global) supply chains (theclimategroup.org). Energy efficiency improvements in (reverse) logistics can therefore result in reduction of emissions. At the same time, it raises the question whether emissions generated by collection vehicles and recovery facilities is acceptable. It is often assumed that e.g. carrying waste over (long) distances is to be avoided. Although apparently trivial, just focusing on the reverse channel is a too narrow scope.

This brings us to an important, but often ignored phenomenon in disposition: the *substitution effect*. Through recovery, energy invested in the forward chain which is locked up in the product (so called GER value), is recaptured. Of course the recovery processes also use energy but generally less than the GER value. For example, the recycling of aluminium is known to use only 10% of the energy when compared with virgin production. The quality of recycled aluminium is equal to virgin and therefore perfect substitution may be assumed (www.bringrecycling.org). Recovery where this substitution applies is referred to as *closed-loop* in this paper. Energy needed for closed-loop remanufacturing amounts in many cases to only 15 to 20 % of the energy needed for production of new products, (Hauser and Lund, 2003; Guintini and Gaudette, 2003).
Often cascade markets in lower segments are developed *in parallel* with primary markets. This is referred to as *open-loop* remanufacturing, which can be very profitable, particularly at the short term. Since open-loops lack energy benefits, in many cases waste incineration, combined with energy recovery, is preferable from an energy perspective when closed loop is not possible. The latest MSW facilities already reach a level of 30% caloric value recaptured (www.ecn.nl). Energy recovery substitutes new energy production and can also improve the overall energy footprint of the closed-loop supply chain.
The substitution effect is not acknowledged by any of the current EPR directives. Moreover, there exist various recovery options as defined in Table 1, with different economical and energy functions in the reverse chain itself. So we need to model the disposition decision carefully.

There is abundant literature on disposition in general, see reviews of Gungor and Gupta, (1999), Srivastava (2007) and the survey on disassembly sequencing by (Lambert, 2003). Often, disposition is optimized on either economical terms, given compliance and technical constraints. Disassembly is governed by a disassembly tree, where optimality depends on cost and revenues, compliance and return quality. In addition, treatment of the collected products is required to remove fractions or groups that contain hazardous materials, such as batteries, printed circuit boards, cathode ray tubes, and external electric cables may pre-fix a minimal disassembly level. The released components are assigned to various treatments. Alternatively, disposition can be based on environmental (LCA) optimization criteria. Combined approaches, referred to as eco-eco, are mostly based on eco-efficiency.

Eco-efficiency has been defined as a general goal of creating value while decreasing environmental impact. Leaving out the normative part of this concept, the empirical part refers to a ratio between environmental impact and economic cost or value (Huppes and Ishikawa, 2005).

There are a number of studies that apply eco-eco modeling to cases, for example to prove the adverse effects of EPR. Hammond and Beullens (2007) show that reuse and recycling in oligopolistic CLSCs are beneficial to turnover and profits and to the reduction of waste but not necessarily to the reduction of virgin materials use. They further show that imposing targets on recovery, combined with increased landfill cost, may decrease virgin material use but at the expense of profits and eventually economic growth. As one of few, Hammond and Beullens (2007) stick to material flows (i.e. recovery quota and virgin material use) as environmental indicators, Krikke et al. (2003) introduce simplified LCA to CLSC modeling, applying both mass - and energy balances. They also show that EPR based regulation can be counterproductive in terms of cost when quota are set too high, but in addition leads to increased energy use.

Quariguasi Frota Neto et. al (2008a) confirm these findings. They develop a model that evaluates Pareto efficiency using Data Envelopment Analysis and Multi-objective Programming. Building on work of Bloemhof, et al. (1996), they apply the model to the European pulp and paper industry, minimizing total cost and an overall environmental impact indicator. They conclude that mandatory recycling quota will not lock out bad environmental solutions and decrease economic efficiency. Quariguasi Frota Neto et. al (2008b) develop a more generic methodology for multi-objective linear problems, minimizing cost, energy and waste. They illustrate the working with a case on the German electronics industry. They find that with reducing landfill, as many waste avoidance acts do, energy use goes up. It also sacrifices profits.

Although not directly driven by mandatory EPR, Kerr and Ryan (2001) discuss a relevant copier remanufacturing case at Fuji Xerox Australia. Next to material and cost savings, they emphasize the reduction of supply chain energy use by a factor of three in the case of a certain type of copier. However, the feasibility of remanufacturing is limited by a number of factors, related to product design.
Zuidwijk and Krikke (2008) show that indeed that the relationship between product eco-design and recovery is crucial also in EPR context. Eco-design serves as an enabler of applying the right, i.e., from an eco-efficiency point of view, recovery options. The paper explicitly

compares the impact of (short term) investments in recovery technology versus the longer term oriented product design changes. Paradoxically, product eco-design has to be justified by CLSC process improvements. And if products are well designed for recovery, many process improvements, including post shredding technologies and X-ray sorting processes, appear not to be needed and relatively simple CLSC processes suffice.
Michelsen et al. (2005) evaluate six different product designs of furniture for different End-of-Life in what they call the extended supply chain, what is in fact the recovery option. They show that (i) there is a strong relationship between product design and disposition choices, (ii) resulting small shifts of applied recovery options can lead to enormous environmental improvements at little or no cost. Environmental impact is measured by extensive LCA based indicators, including several that deal with energy related emissions.

One may conclude from the literature that environmental impact can be measured by single- or multi-criteria models. Michelsen et al. (2005) use nine environmental indicators. Bloemhof et al. (1996) and Quariguasi Frota Neto et. al (2008a) use one environmental indicator, but in Quariguasi Frota Neto et. al (2008b) they balance waste and CED (cumulative energy demand) with economics. Kerr and Ryan (2001) emphasize energy but also discuss material use, water use, landfill and CO2. Clearly, the more parameters the bigger the data problem, which poses a serious challenge in all environmental (and closed loop supply chain) studies.
Model simplification can help in this respect. We postulate that the energy footprint in itself is a reliable overall indicator of environmental soundness of a closed loop supply chain. The substitution principle implicitly enhances high quality recovery, since recovery must be fully competitive with virgin production, either by remanufacturing, recycling or energy options. Henceforth, recovery volume or reduced virgin production as environmental indicator are not needed in our approach. Moreover, since energy use is the root cause of emissions we do not model e.g. CO2 or NOx output separately.

Often, the saving of energy automatically creates sufficient economic benefits as well. In some cases however, priority sequences from an economic point of view are different from the one from an energy point of view. For example, open-loop remanufacturing may be more economically viable than other options due to parallel market development, but increases overall energy use.
Economic proceeds and cost and modeled covering the full CLSC in this paper. Economics can be modeled as direct cost and revenues (Bloemhof et al., 1995), life cycle based (Michelsen et al., 2005) or as net profits (Zuidwijk and Krikke, 2008). Although not without trouble, many supply chain systems today are able to produce reasonable economics data.

The objective of this research is to discover new policy approaches that affect disposition decisions in such a way that energy footprints improve and that businesses are not unnecessarily obstructed in achieving their economic objectives. We anticipate that this can be achieved solely by exploiting the substitution effect.

We will show that recovery quota have limited or even an (unintended) adverse impact and energy based policies prove better. In particular, we show how to determine a preference ordering of recovery options depending on a number of context dependent factors and that it indeed vary among realistic cases. In doing so however, we may run into trade-offs, hence economic objectives conflict with energy reduction. By identifying the Pareto efficiency frontier in the analysis of our model results, we present the trade-offs in an insightful way. Thereby we use analytical techniques for maximal lucidity and minimal data requirements. It also enables (visual) sensitivity analysis to ease the tensions between energy and economical goals by aligning optimal priority sequences of recovery options.

In Section 3 we will elaborate how we modeled the closed-loop supply chain as why we do it, thereby taking into account lessons learned from the literature as described above.

3. A generic analytical model

Given our objective to evaluate EPR policies and provide recommendations for improvement, and not to discuss business strategies in detail, we model the return and disposition processes as flows in a dynamical system. In particular, individual products and disassembly bills of materials are not modeled explicitly. For our purposes it is not necessary to distinguish between different degrees of disassembly. We shall describe the dynamical system in mathematical detail in Section 3.1.

Because closed supply chains follow the product life cycle over time, our model comprehends both the forward and reverse supply chain, where the latter has four recovery options, including disposal with energy recovery. We consider closed-loop and open-loop *remanufacturing* as it serves different markets and has different environmental and economical impacts. Closed-loop remanufactured - and newly manufactured products are assumed to be perfect substitutes since reuse takes place in the original supply chain. Open-loop remanufactured products or materials are sold in alternative, cascade markets, not competing with primary sales. Hence, parallel markets can develop where closed-loop remanufacturing exploits the substitution effect and open-loop does not. In other words, demand in these markets is mutually independent as they involve e.g. different social classes or other geographic areas. Demand in the original market is set by exogenous sales, while demand in alternative markets is considered in-exhaustive. This can be justified for developing markets which fully depend on the supply of open-loop remanufactured items.

Material recycling is required to obtain the materials back. Because recycling is assumed to be competitive with virgin materials, a substitution effect exists here as well. To avoid having to down-cycle, energy recovery is introduced as this form of disposal is competitive with virgin energy production. *Disposal* is always possible and always combined with this energy recovery, hence also contributes to achieving a better energy profile, and is therefore a good alternative.

We model the closed-loop supply chain as a dynamical system. However, under mild conditions, this model can be reformulated as a simple network flow problem which can be solved explicitly. By assuming that closed-loop remanufactured items can be sold immediately and that new production can serve the market immediately, inventories of new production can be put equal to zero. Similarly, by assuming that recovery channels are incapacitated and that market prices are constant, returns inventories can also be assumed zero. Further, we assume zero disposal cost as incinerators operations are fully covered by energy recovery proceeds.

Using these assumptions, we can optimize energy use and net profit constrained by recovery quota with analytical expressions. By considering parameters that do not evolve in time, we further simplify the problem and minimize data requirements for the case studies.

In our eco-eco analysis, we address energy and emissions related to (economical) disposition decisions in a compact manner. We model energy use of all supply chain processes and net revenues of both new and remanufacturing (open-loop and closed-loop), material recycling and disposal. The trade-off between energy use and net revenues will be supported by considering the Pareto efficiency frontier.
Quariguasi Frota Neto et. al (2008b) compares pros and cons of single ratio, weighting LP, multi-objective and a newly introduced eco-topology method built on the Pareto concept. They show that the latter is more feasible to show the full spectrum of options to be considered in eco-efficiency trade-offs.

In our model, we consider the frontier of Pareto optimal solutions with respect to economic revenues and energy consumption of recovery strategies. Recovery strategies are expressed in terms of the *priority sequence* in application of different recovery options, bounded by technical feasibility and EPR policy targets.

Whereas technical constraints will be seen as a given parameter, we will develop scenarios with various policy instruments implemented as constraints. The given technical parameters could be influenced by policies other than disposition related, such as Design for X and collection. The feasibility for remanufacturing is constrained by a return feasibility parameter, representing both quality and market acceptance. Feasibility for recycling is also expressed by a parameter. We will discuss these in a sensitivity analysis.

3.1 Model description

We describe a system of flows and inventories of products at several stages in their lifecycle. Figure 1 represents our CLSC model as a linear dynamical system. New production $n(t)$ and closed-loop remanufactured items $q^c(t)$ feed sales $s(t)$. The inventory level of new and remanufactured items is denoted by $J(t)$. We assume that remanufactured items in the closed-loop flow $q^c(t)$ are as good as new, as opposed to the remanufactured items $q^o(t)$ in the open-loop flow. The installed base $B(t)$ is fed by sales and releases returns $r(t)$. The inventory of returned items is denoted by $I(t)$. The return flow is possibly directed towards closed-loop and open-loop remanufacturing flows as indicated above, a waste flow $w(t)$ which is being incinerated and henceforth generates energy, and a flow $m(t)$ of products that are recycled.

Figure 1: CLSC model displayed as a dynamical system

The flow equation

$$J'(t) = n(t) + q^c(t) - s(t) \tag{0.1}$$

expresses that new production and closed-loop remanufactured items feed inventory, while sales is replenished from this inventory. The inventory level should be positive at all times, i.e., $J(t) \geq 0$.

The installed base $B(t)$ is fed by sales and releases returns $r(t)$ according to

$$B'(t) = s(t) - r(t)\,. \tag{0.2}$$

This process is assumed to be exogenous. In particular, we write

$$r(t) = \int_{t_0}^{t} g(t,x)s(x)\,dx\,, \tag{0.3}$$

where $g(t,x)$ indicates the fraction of sales at time x that is returned at time t. If we write

$$B(t) = \int_{t_0}^{t} G(t,x)s(x)\,dx\,, \tag{0.4}$$

then (0.2) results in

$$G(t,t) = 1, \qquad \frac{\partial G}{\partial t}(t,x) = -g(t,x)\,. \tag{0.5}$$

In line with these requirements, we may interpret $G(t,x)$ as the fraction of sales at time x that still resides in the installed base at time t. The returns feed the inventory $I(t)$ which on its turn feeds waste flow $w(t)$, open-loop flow $q^o(t)$ and closed-loop flow $q^c(t)$ of items that will be remanufactured, and the material recycling flow $m(t)$. These flows are restricted by rates that describe technical feasibility of return options:

$$m(t)+q^{o}(t)+q^{c}(t)\le \mu(t)\cdot r(t)\,, \tag{0.6}$$

where $\mu(t)$ denotes the fraction of returns that can be forwarded to material recycling. The return fractions that are appropriate for open-loop remanufacturing and closed-loop remanufacturing read $\kappa^{o}(t)$ and $\kappa^{c}(t)$, respectively. The technical feasibility constraints read:

$$q^{o}(t)+q^{c}(t)\le \kappa^{o}(t)\cdot r(t) \tag{0.7}$$

$$q^{c}(t)\le \kappa^{c}(t)\cdot r(t) \tag{0.8}$$

Material recycling, open-loop remanufacturing, and closed-loop remanufacturing are recovery options that have progressive input requirements, which is modeled through $0\le \kappa^{c}(t)\le \kappa^{o}(t)\le \mu(t)\le 1$ and the constraints (0.6) - (0.8).

Kept returns inventory $I(t)$ results from balancing returned products and products forwarded to material recycling and remanufacturing, and disposal, and should be positive, i.e.,

$$I'(t)=r(t)-q^{c}(t)-q^{o}(t)-m(t)-w(t),\quad I(t)\ge 0\,. \tag{0.9}$$

We will also consider a constraint which relates to a policy measure of the current EPR directives. Other possible policy measures will be discussed in Section 3.3. The directives require a fraction T of returned volume to be recovered. The excess amount of recovered materials relative to the target T is put equal to $K(t)$. It is governed by

$$K'(t)=m(t)+q^{c}(t)+q^{o}(t)-T\cdot r(t)\,, \tag{0.10}$$

and it must be positive, i.e., $K(t)\ge 0$. The directive sets another target for the returned volume to be either recycled or used for energy recovery by incineration. In our model, we assume that *all* product returns will be either recovered or incinerated so that we do not need to consider this target explicitly.

The decision variables are $n(t),w(t),m(t),q^{c}(t),q^{o}(t)$. We identify two objectives, namely revenue rate

$$\begin{aligned}\rho(t)=&\ p\cdot s(t)-c_q^c\cdot q^{c}(t)+(\rho_q^o-c_q^o)\cdot q^{o}(t)+(\rho_m-c_m)\cdot m(t)-c_w\cdot w(t)\\&-c_r\cdot r(t)-c_n\cdot n(t)-h_rI(t)-h_nJ(t)\end{aligned}, \tag{0.10}$$

and energy consumption rate

$$\varepsilon(t)=\varepsilon_n\cdot n(t)+\varepsilon_s\cdot s(t)+\varepsilon_r\cdot r(t)+\varepsilon_m\cdot m(t)+\varepsilon_q^c\cdot q^{c}(t)+\varepsilon_q^o\cdot q^{o}(t)-\varepsilon_w\cdot w(t)\,. \tag{0.11}$$

Depending on the perspective (policy makers, OEM or SC balanced) weights could be associated with these outputs. However, in this study we will not assign weights but consider the Pareto frontier instead. Notation used in the formulas above is summarized in the Appendix I.

Quantities y in the tables that depend on time t are considered functions $y(t)$ in continuous time starting at $t_0 \geq -\infty$. We assume that $B(t_0) = I(t_0) = J(t_0) = K(t_0) = 0$.

The dynamical model covers the full scope of the closed-loop supply chain, which may serve elaborate disposition analyses. We postulate generalizability to other CLSC as long as EPR and the substitution effect apply. It also proves to be complex if not impossible to solve analytically. As mentioned earlier, analytical solutions enable a lucid analysis, reduce data requirements and avoid lengthy simulation or optimization runs. So we start simplifying in 3.2. after we model our policy measures in 3.3 .

3.2 Model analysis

We now further analyze the model in order to achieve simplifications. We claim that if

$$\kappa^c(t) \cdot \int_{t_0}^{t} g(t,x)s(x)\,dx \leq s(t) \tag{0.12}$$

for all $t \geq t_0$, then

$$I(t) = 0, \qquad t \geq t_0 . \tag{0.13}$$

This results comes down to the zero-inventory property in dynamic inventory control; see for example (Zipkin, 2000).

We assumed that $I(t_0) = 0$. If for some $t \geq t_0$, it holds true that $I'(t) > 0$, then not all returns are forwarded immediately to the recovery options. As the open-loop recovery options are assumed to have unlimited capacity, and as, by (0.8) and (0.12), sales absorbs all closed-loop remanufacturing flows, i.e., $q^c(t) \leq \kappa^c(t) \cdot r(t) \leq s(t)$, this delay causes unnecessary holding costs.

Under condition (0.12), we also find that

$$J(t) = 0, \qquad t \geq t_0 \tag{0.14}$$

If $J'(t) > 0$ or

$$s(t) < n(t) + q^c(t), \tag{0.15}$$

then with $q^c(t) \le s(t)$, we find that $n(t) > 0$. In other words, we are producing new items for inventory. As new item production capacity is unlimited and can be deployed immediately, this results in unnecessary holding costs.

The two observations above allow us to fix two decision variables. Indeed, by (0.13), we arrive at

$$w(t) = r(t) - q^c(t) - q^o(t) - m(t), \tag{0.16}$$

and (0.14) results in

$$n(t) = s(t) - q^c(t). \tag{0.17}$$

With sales fixed, observe that virgin production and closed-loop remanufacturing are complementary and competing alternatives.

We introduce the notation

$$Y(t) = \int_{t_0}^{t} y(x)\,dx,$$

and apply this to the remaining decision variables $m(t), q^c(t), q^o(t)$ and objective functions $\rho(t), \varepsilon(t)$, and introduce the new decision variables $M(t), Q^c(t), Q^o(t)$ and objective functions $R(t), E(t)$. Observe that $R(t)$ does not refer to the returns, but to revenues. We will not apply this notation to $r(t)$; it will turn out we actually don't need to. The model now reads

$$M(t) + Q^o(t) + Q^c(t) \le \int_{t_0}^{t} \mu(x) \cdot r(x)\,dx \tag{0.18}$$

$$0 \le Q^o(t) + Q^c(t) \le \int_{t_0}^{t} \kappa^o(x) \cdot r(x)\,dx \tag{0.19}$$

$$0 \le Q^c(t) \le \int_{t_0}^{t} \kappa^c(x) \cdot r(x)\,dx \tag{0.20}$$

by (0.6) - (0.8), respectively. The directive target (0.10) states that

$$M(t) + Q^c(t) + Q^o(t) \ge T \cdot \int_{t_0}^{t} r(x)\,dx. \tag{0.21}$$

We assume feasibility of this target by setting

$$T \cdot \int_{t_0}^{t} r(x)\,dx \le \int_{t_0}^{t} \mu(x) \cdot r(x)\,dx. \tag{0.22}$$

The cumulative revenue now reads

$$R(t) = R_0 + (c_n - c_q + c_w) \cdot Q^c(t) + (\rho_q^o - c_q + c_w) \cdot Q^o(t) + (\rho_m - c_m + c_w) \cdot M(t) , \tag{0.23}$$

where the sunk revenues are given by

$$R_0 = (p - c_n)S(t) - (c_r + c_w)\int_{t_0}^{t} r(x)dx . \tag{0.24}$$

Sunk revenues consist of sales revenues minus costs of handling returns and the cost of forwarding all returns to waste incineration. Therefore, in the optimization procedure, the opportunity costs of not forwarding returns to waste incineration will be considered. Observe that sunk revenues depend on sales. By inserting (0.3), we make this explicit:

$$R_0 = (p - c_n)\int_{t_0}^{t} s(x)dx - (c_r + c_w)\int_{t_0}^{t}\int_{t_0}^{x} g(x, y)s(y)dydx . \tag{0.25}$$

Cumulative energy consumption reads

$$E(t) = E_0 + (\varepsilon_q^c - \varepsilon_n - \varepsilon_w) \cdot Q^c(t) + (\varepsilon_q^o - \varepsilon_w) \cdot Q^o(t) + (\varepsilon_m - \varepsilon_w) \cdot M(t) , \tag{0.26}$$

where sunk energy consumption is given by

$$E_0 = (\varepsilon_n + \varepsilon_s)S(t) + (\varepsilon_r - \varepsilon_w)\int_{t_0}^{t} r(x)dx . \tag{0.27}$$

Here sunk energy consumption consists of energy consumption associated with new production and sales, and energy consumption (may be negative) of handling returns and forwarding returns to waste incineration. As a result, in the optimization procedure, the energy gain of using closed-loop remanufacturing compared to new production will be evaluated, and energy consumption of recovery processes compared to waste incineration will be evaluated. Instead of considering the total revenues and energy consumption, we will compute the revenues and energy consumption per kilogram returned product. We do this by dividing $R(t), E(t)$ by $\int_{t_0}^{t} r(x)dx$, i.e., by defining

$$\overline{\rho}(t) = \frac{R(t)}{\int_{t_0}^{t} r(x)dx}, \quad \overline{\varepsilon}(t) = \frac{E(t)}{\int_{t_0}^{t} r(x)dx}, \quad \overline{y}(t) = \frac{Y(t)}{\int_{t_0}^{t} r(x)dx} , \tag{0.28}$$

where $Y = M, N, Q^c, Q^o, W$. Moreover, we will not consider sunk revenues and sunk energy consumption R_0, E_0 as these quantities do not impact the decisions. It turns out that one may compute the optimal solutions without specifying sales and installed base size, hence total return volume. We summarize the coefficients of the objective functions in Table 3 and discuss the interpretations.

Table 3: Coefficients of the decision variables in objective functions about here

At six positions, numbered 1 through 6 in Table 3, one can determine the order preference of recovery options in terms of inequalities between these coefficients. For each position, we consider and interpret one possible inequality. The converse inequalities can be interpreted accordingly.

1. $c_n - c_q^c + c_w \geq \rho_q^o - c_q^o + c_w$ holds true whenever $c_n - c_q^c \geq \rho_q^o - c_q^o$, i.e., whenever per kilogram cost benefits of closed-loop remanufacturing, as opposed to new production, outweighs profits from open-loop remanufacturing.
2. $\rho_q^o - c_q^o + c_w \geq \rho_m - c_m + c_w$ holds true whenever $\rho_q^o - c_q^o \geq \rho_m - c_m$, i.e., whenever per kilogram profit of open-loop remanufacturing exceeds recycling profit.
3. $\rho_m - c_m + c_w \geq 0$ or $\rho_m - c_m \geq -c_w$ holds true whenever per kilogram incineration costs are higher than recycling costs (negative recycling profits).
4. $0 \leq \varepsilon_q^c - \varepsilon_n + \varepsilon_w$ or $\varepsilon_n - \varepsilon_w \leq \varepsilon_q^c$ holds true whenever per kilogram new production energy consumption, mitigated by incineration energy gain, is less than closed-loop remanufacturing energy consumption.
5. $\varepsilon_q^c - \varepsilon_n + \varepsilon_w \leq \varepsilon_q^o + \varepsilon_w$ holds true whenever $\varepsilon_q^c - \varepsilon_n \leq 0 \leq \varepsilon_q^o$, i.e., whenever per kilogram new production energy consumption exceeds closed-loop remanufacturing energy consumption, and when open-loop remanufacturing consumes energy.
6. $\varepsilon_q^o + \varepsilon_w \leq \varepsilon_m + \varepsilon_w$ or $\varepsilon_q^o \leq \varepsilon_m$ corresponds to the case where open-loop remanufacturing consumes less energy per kilogram than material recycling.

As said, for these six positions, the converse inequalities may also hold true. Observe that these inequalities express preference orders of recovery options with respect to the two objectives of maximizing profit $\overline{\rho}(t)$ and minimizing energy consumption $\overline{\varepsilon}(t)$. For the inequalities as given above, the preference order reads $\overline{q}^c(t) \succ \overline{q}^o(t) \succ \overline{m}(t) \succ \overline{w}(t)$ for $\overline{\rho}(t)$ and $\overline{w}(t) \succ \overline{q}^c(t) \succ \overline{q}^o(t) \succ \overline{m}(t)$ for $\overline{\varepsilon}(t)$, where $A \succ B$ stand for "A is to be preferred over B". Although we need not introduce waste incineration $\overline{w}(t)$ as a separate decision variable, its revenue and energy production contribution is relevant, as can be seen from the discussion on the six positions.

3.3 Modeling of policy measures

As discussed in Section 1, an alternative directive may deploy policy measures in order to influence the use of recovery options by industry. EPR may deploy alternative measures that impact the performance of the favorable recovery options or constrain the use of other recovery options. We shall review these measures considering two archetypical recovery options; a "bad" option B, and a "good" option G, where $\rho_B - c_B > \rho_G - c_G$ and $-\varepsilon_B < -\varepsilon_G$. Observe that the bad option consumes more energy (or produces less) but generates more revenues. We only consider this situation as options which consume more energy and generate less revenue do not require any attention. The policy will aim to promote the recovery option G by providing incentives or constraints. These measures have critical values where bad option B is rendered either unfavorable or even unfeasible; see Figure 2. We will apply this to WEEE in the next section.

Figure 2: Impacts of policy measures.

1. Target on good option G

The EPR policy may deploy a target $0 \le T_w \le 1$ on the weight fraction of returns recovered through good option G. It makes recovery of returns through recovery option B infeasible beyond the weight percentage $(1-T_w)\times 100\%$. The present WEEE directive deploys such a target for a collective of recovery options such as material recycling and, to some extent, remanufacturing. The impact of this policy measure is depicted by means of a white feasible area which is to the left and above the shaded area (1). The boundary of the shaded area is populated by arrows that direct towards the feasible area. The implementation of this policy measure in the model is given by (0.21).

2. Energy Tax

The WEEE directive may introduce an energy tax τ_ε per energy unit that will further diminish the revenues of recovery options that consume a lot of energy. Such a measure will render recovery option B unfavorable when

$$\tau_\varepsilon \ge \frac{(\rho_B - c_B) - (\rho_G - c_G)}{\varepsilon_B - \varepsilon_G}.$$

The impact of the energy tax is denoted by arrow (2) which indicates that the bad option becomes less profitable. The modelling of this policy measure involves the augmentation of the objective $\overline{\rho}(t)$ with $-\tau_\varepsilon \cdot \overline{\varepsilon}(t)$.

3. Tax on bad option B

The WEEE directive may put a tax τ_B per weight unit recovered through option B. This measure will leave recovery option B unfavorable for

$$\tau_B \ge (\rho_B - c_B) - (\rho_G - c_G).$$

The impact of the tax is denoted by arrow (3) which coincides with arrow (2). In order to implement this policy measure in the model, the term $-\tau_\varepsilon \cdot \overline{b}(t)$ needs to be added to the objective $\overline{\rho}(t)$, where $\overline{b}(t)$ stand for the relative amount of the bad option flow, e.g. $b = q^o$ (and $B = Q^o$).

4. Subsidy on good option G

The WEEE directive may provide a subsidy r_G per weight unit recovered through option G. This measure will make recovery option G favorable for

$$r_G \geq (\rho_B - c_B) - (\rho_G - c_G).$$

The impact of the subsidy is denoted by arrow (4) which enhances the profitability of good option G. Now we need to add the term $+r_G \cdot \overline{g}(t)$ needs to be added to the objective $\overline{\rho}(t)$, where $\overline{g}(t)$ stand for the relative amount of the bad option flow, e.g. $g = q^c$ (and $G = Q^c$).

5. Target on energy consumption

The WEEE directive may constrain the amount of energy used for recovery per weight unit of returns by a target $T_\varepsilon \geq 0$. The energy target will be effective when $-\varepsilon_B < T_\varepsilon \leq -\varepsilon_G$, and it will leave recovery option B infeasible beyond a weight percentage of returns equal to

$$-\frac{\varepsilon_G + T_\varepsilon}{\varepsilon_B - \varepsilon_G}.$$

The impact of this target is depicted by means of a white feasible area which is above the shaded area (5). The boundary of the shaded area is populated by arrows that direct towards the feasible area. Observe that Figure 2a also illustrates the combined use of policy measures (1) and (5) by indicating the white feasible area to the left and above the shaded areas (1) and (5). Modeling requires the additional constraint

$$-\overline{\varepsilon}(t) \geq T_\varepsilon \qquad (0.29)$$

6. Target based tax or subsidy

EPR directives may set an energy production target T_ε and define a tax τ_ε and subsidy r_ε per unit of energy which are effected as follows:

$$(\varepsilon + T_\varepsilon)^- r_\varepsilon + (\varepsilon + T_\varepsilon)^+ \tau_\varepsilon \qquad (0.30)$$

The impact of this policy measure is demonstrated in Figure 2 by arrows (6). The target based tax or subsidy has an effect in the case when $-\varepsilon_B < T_\varepsilon < -\varepsilon_G$, and effects the economic viability of the bad option compared to the good option when $(\varepsilon_G + T_\varepsilon)^- r_\varepsilon + (\varepsilon_B + T_\varepsilon)^+ \tau_\varepsilon \geq (\rho_B - c_B) - (\rho_G - c_G)$; see Figure 2. To incorporate this policy measure in the model, we need to augment $\overline{\rho}(t)$ with (0.30).

4. Case studies results

Advances in technologies, shortening life cycles and globalization of economies have led to a massive growth of discarded consumer electronics products. As explained in Section 1, several countries apply EPR to WEEE.

In this section we present the model results for the business cases by using the data from industry. As returns are normalized for model simplification, so are results. For each specific instance of a closed-loop supply chain involving a specific product or part, one should be able to fix the six inequalities in Table 3 and solve the model. We will do this for a number of cases represented by example business cases.

Table 4 about here, Recovery options per case

Table 4 presents the recovery options that apply to each of the five cases. Section 4 presents results for the current situation, where quotas are imposed according to the directive. For each case we calculate the priority sequence of available recovery options (decision variables) both on the economic and on the energy objectives.

As mentioned before, the model optimizes economic and energy performance of the supply chain. The results are depicted in graphs where revenues $\overline{\rho}(t)$ and energy production $-\overline{\varepsilon}(t)$ are depicted horizontally and vertically, respectively. Note that normalization has led to results per kg returned product. By applying our model we find a frontier of Pareto optimal solutions for each case. These solutions balance the energy-best solution and the economic optimum, while taking into account technical constraints. We shall study the impact of policy measures discussed in Section 3.3 on these Pareto frontiers for each case separately.

4.1 Case-by-case analysis

In this section, we shall discuss the results case by case. In 4.2 we discuss the impact of the proposed policy approaches in more detail.

The TV case is first, being the simplest with only material recycling and disposal as options. To improve profits open-loop remanufacturing is researched in the CRT monitor case but unfortunately energy objectives interfere with economic objectives. The more eco-designed product copier is then analyzed applying the same recovery options. A closed-loop case on spares serves to find more synergy between economics and energy.The industrial fridge case reflects a situation where an eco-designed product can apply all recovery options. All cases are subjected to the proposed policy approaches, and current EPR quota.

TV Case

In the TV case, only material recycling and waste incineration apply. As disposal is combined with energy recovery, both recovery options contribute to EPR-quota, as long as there is not too much allocated to waste. In Figure 3 we see that the (Pareto) optimal solution consist of a single point where $\overline{m}(t) = \mu$ and $\overline{w}(t) = 1 - \mu$, i.e., as can be inferred from Table 5 considering the preference order $\overline{m} \succ \overline{w}$, we recycle as much returns as possible, the remainder is waste incinerated. EPR-quotas are automatically met since all recovery is economically viable and energy efficient. However, profits are relatively low, and we continue with a case including open-loop remanufacturing to boost profits. We do so because the natural instinct of industry is to hammer out more profitable recovery options.

Table 5: TV Case; Figure 3: TV Case

CRT Monitor Case

Table 6 presents the data of the CRT monitor case which indicate that material recycling results in a relative energy gain while it represents costs. Forwarding all returns to waste recycling $(\overline{q}^o, \overline{m}) = (0,0)$ increases energy consumption, but no relative costs are incurred. However, this option does not constitute a Pareto optimal point. Forwarding all returns to recycling constitutes a Pareto optimal solution $(\overline{q}^o, \overline{m}) = (0, \mu)$ with high energy production but with negative revenues. By forwarding returns to open-loop remanufacturing as much as possible, revenues are created at the cost of increased energy consumption. Two Pareto optimal points are established by sending the remainder to material recycling as much as possible $(\overline{q}^o, \overline{m}) = (\kappa^o, \mu - \kappa^o)$ or to waste incineration $(\overline{q}^o, \overline{m}) = (\kappa^o, 0)$. The continuum of balancing between the three Pareto optimal alternatives constitutes two lines of Pareto optimal solutions; see Figure 4. We find that the priority sequence in Table 6 based on energy is the reverse of the economical priority. All policy measures can be used to favor material recycling above open-loop remanufacturing or waste incineration. For example, by setting the energy quota at zero, i.e., $T_\varepsilon = 0$, we get that the Pareto frontier consists of the line between endpoints $(\overline{q}^o, \overline{m}) = (0, \mu)$ and $(\overline{q}^o, \overline{m}) = (t, \mu - t)$, where

$$t = \min\left(\frac{\mu(\varepsilon_w + \varepsilon_m)}{\varepsilon_m - \varepsilon_q^o}, \kappa^o \right) \approx 0.014\,;$$

see Figure 4.

To verify findings, we do another case with the same recovery options, namely copiers. These products are eco-designed and are expected to perform better and have more synergy between energy and economic goals.

Table 6: CRT Monitor Case; Figure 4: CRT Monitor Case

Copier Case

Unfortunately, the conclusions for this case are similar, as Figure 5 shows. Open-loop remanufacturing is viable from an economic perspective, but is unattractive when considering energy consumption; see Table 7. As a result, the Pareto optimal solutions in Figure 5 are a trade-off between open-loop remanufacturing $(\overline{q}^o, \overline{m}) = (\mu, 0)$ and material recycling $(\overline{q}^o, \overline{m}) = (\mu - \kappa^o, \kappa^o)$. Although overall results are indeed better, there appears to be a fundamental conflict between energy and economical objectives in open-loop remanufacturing. We find that in both the CRT monitor and copier case, virgin production is not reduced, read substituted. In other words: the conflict between energy and economics is not removed by eco-design because closed loop remanufacturing is not applied.

The good news is that eco-design does lead to better overall performance, but paradoxically, a major consequence is that the current quotas have no impact on the solutions, as both material recycling and open-loop remanufacturing comply with these quotas. Modified quotas or other policy measures that differentiate between the different options would have an effect, see 4.2. As in the simple TV case, Pareto optimal decisions are purely driven by energy and money.

Table 7: Copier Case; Figure 5: Copier Case

Spare Parts Case

To find more synergy between both objective functions we present a spare parts case with closed-loop remanufacturing and material recycling as recovery options; see Table 8 and Figure 6.In this straightforward case, only one Pareto-optimal solution is found, again illustrated by a single dot. One closed-loop remanufactures as much as possible, and then one recycles as much as possible. Policy measures are not required here. Clearly, there is no open-loop remanufacturing option available, so there is no temptation to apply this. In order to further understand trade-offs between closed-loop and open-loop remanufacturing, we now present a case in which all recovery options are applicable. This is the industrial fridge case.

Table 8: Spare Parts Case; Figure 6: Spare Parts Case

Industrial fridge Case

It appears from Table 9 that open-loop remanufacturing again generates higher revenues than the other options, while it develops a profitable market completely independent from primary sales. Overall profits are much higher than in closed-loop remanufacturing due to additional turnover from the alternative markets. Here the Pareto optimal set corresponds with balancing between cost efficient open-loop remanufacturing $(\overline{q}^c, \overline{q}^o, \overline{m}) = (0, \kappa^o, \mu - \kappa^o)$ and energy efficient closed-loop remanufacturing $(\overline{q}^c, \overline{q}^o, \overline{m}) = (\kappa^c, 0, \mu - \kappa^c)$. The option material recycling $(\overline{q}^c, \overline{q}^o, \overline{m}) = (0, 0, \mu)$ stands in the middle, but does not constitute a Pareto Optimal point; see Figure 7. The fundamental conflict is re-confirmed. Again, the recovery quotas do not play any role in the decision making, and more differentiated policy measures are required to put closed-loop remanufacturing as the more favorable one.

Table 9: Industrial Fridge Case; Figure 7: Industrial Fridge Case

4.2 Discussion

Effectiveness of policies

For the assessment of the impacts of the six policy measures outlined in Section 3.3 on each of the cases, we take the marginal revenues and energy production from Table 3. As a result, we obtain the results as displayed in Table 10.

Table 10: Policy measures in cases

The first two columns in Table 10 clarify the good and bad options at hand. The third column explains whether the target on the good option has an impact ("applicable") or not ("not applicable"). The column on "energy tax" provides $\frac{(\rho_B - c_B) - (\rho_G - c_G)}{\varepsilon_B - \varepsilon_G}$, which gives a lower bound for effective tax rates (in euro) per kg of returned and processed materials. The fourth column on "tax on bad option" or "subsidy on good option" provides $(\rho_B - c_B) - (\rho_G - c_G)$, which gives a lower bound for tax rates or subsidy rates to be effective. For the "energy target" and the "target based energy tax", we provide the interval $[-\varepsilon_B, -\varepsilon_G]$ in the fifth and sixth column, which indicates the range of values of an effective energy target. Together with the value $(\rho_B - c_B) - (\rho_G - c_G)$ in the fourth column, an assessment can be made of effective energy tax rates (which are subsidies when energy production exceeds the target). Observe that the policy measures do not apply to the TV case and Spare parts case, as no good options can be contrasted with bad options in those cases. This need not be a problem, as one may argue that no governmental interference is required. Other measures, to be discussed later, are needed to boost their eco-eco performance.

For the other cases goes that open-loops must be discouraged to reduce energy use. This could be achieved by selective targets on good options (1), but as we see this is complicated because we have multiple Good and Bad options for some of the cases. Since we want to reduce energy use, why not directly address this?

Due to the strong assumption of parallel markets, a conflict of objectives become apparent in 4.1: open-loop remanufacturing in cascade markets does not contribute to environmental objectives but is very profitable. Profitability is simply caused by the growth of overall sales volume. However, weakening the assumption of mutually exclusive (independent) markets, and hence allowing for the possibility for primary market cannibalization, would also reduce the economic viability of open-loop remanufacturing.

Policy approaches that (further) weaken the economic viability of open-loop options should be enhanced. A general energy tax (2) might be feasible, but obvious criticism is that now all options are punished, although open-loop the most. Taxes on bad options (3) can be implemented, where open-loop remanufacturing represents bad. The income generated by this could be spent to subsidize good options (4). To ascertain Good and Bad options might be complicated here as well and hence, the application of energy targets (5) works better, because it allows for more nuanced trade-offs between recovery options. It requires a formula that determines how to set the threshold *per case, i.e. product type*. Using this, one could strengthen enforcement by introducing a tax on energy exceeding this target level (6). Tax incomes can be transferred to closed loop supply chains that eco-perform above average. Setting this target level requires the use and constant adaptation of target values . In fact, it is a moving target as innovation progresses in the closed loop supply chain. Policy measure (6) combines the other measures into one approach, avoiding the negative aspects of each individual measure.

When implementing good regulation , the results can be rather positive: taking an energy perspective stimulates closed-loop, thereby creating environmental benefits and generating economic proceeds. However, when looking at the policy approaches presented, criticism is possible.

The eco-efficiency optimum is context dependent and moreover might change over time as product and process parameters change. Moreover, in our review of the case studies, the suggested (universal) policy alternatives will be non-effective in some of these cases, even though energy based.

Adaptation can be achieved on the level of business cases, such that policies create incentives geared towards compliance to environmental performance targets. The policy measures proposed (still) direct disposition choices *given* the Pareto curve. In other words, they merely restrict the room or solutions space. The fact that they are more effective than recovery quota is because they direct solutions in the right direction on a given curve. But what if we *change* the curve? The cases analysed have an increasing degree of Design for X, where eco-designed products clearly have an advantage, provided closed loops are applied. This gives us a handle to do sensitivity analysis.

Sensitivity Analysis

A sensitivity analysis on the main parameters in the model, can be done visually. A sensitivity analysis on the technical feasibility parameters κ^{o}, κ^{c} does not apply to the TV case. In all other cases, the effect of applying remanufacturing instead of recycling can be viewed in Figures 4, 5, 6, and 7, the line segment between the points $(\overline{q},\overline{m})=(0,\mu)$ and $(\overline{q},\overline{m})=(\kappa,\mu-\kappa)$ can be varied in length to get an idea of the possible impact of varying κ. In Figure 4, the segment between the points $(\overline{q},\overline{m})=(\kappa,\mu-\kappa)$ and $(\overline{q},\overline{m})=(\kappa,0)$ needs to be translated accordingly. In Figure 7, two line segments can be identified, related to $\kappa=\kappa^{o}$ and $\kappa=\kappa^{c}$. Observe that the business cases as such represent different parameter configurations with respect to revenues and costs and henceforth provide a scenario analysis of realistic parameter settings.

As sensitivity analysis shows, performance improvement policies, those who move or even change the curve, would have to impact the coefficients and/or parameters of the model. Table 3 depicts the coefficients of the performance, both economical and energy wise, per recovery option. Changes in these coefficients would severely change and possibly improve potential in the trade-offs to be made. Moreover, the parameters κ^{c} and μ may not influence results per kg returned, but clearly impact overall system performance in that total flows allocated to closed-loop remanufacturing and material recycling can increase. Both coefficients and parameters are dependent on collection as well as DfX. Policy makers should perhaps focus on making enablers of closed loop supply chains more endogenous and let the market subsequently do the ‘EPR work’. Note that also these types of approaches are still based on the energy perspective and the substitution effect.

The bigger picture

Finally, what is the impact of our work in view of the environmental emissions that we started with? It must be mentioned beforehand that the relationship between energy use and emissions such as CO2 is complicated and only estimated roughly here. Quariguasi Frota Neto et. al (2008b) and theclimategroup.org calculate that about 0.13 to 0.20 kg CO2 eq. is emitted per MJ energy used in the (closed loop) EEE supply chain. If we apply this to our results and scale it up the global impact can be assessed as follows. For the United States alone, where about 10 million tons of WEEE are generated annually, our results would mean a ballpark reduction 130.000 million kg of CO2 eq. on emissions per year. For Europe, it would equal 91.000 million kg of CO2 eq. and for Japan, the third largest WEEE generator, almost 65.000 million kg of CO2 eq. can be saved. Or in total 286 million ton CO2 eq. per year. Again, ballpark estimates are that about 2400 million tons of embodied CO2 in EEE supply chains (theclimategroup.org). Adding up our estimates, 286 million ton of CO2 eq. savings equals about 1% of total global CO2 emissions in EEE supply chains. Allowing open-loops would lead to an *increase* of about 100 million ton of CO2 eq. or 0.33%. These ballpark estimates could lead to the conclusion that the contribution of closed loop in CO2 reduction is somewhat marginal, however we should bear in mind that solving this puzzle requires many little pieces.

5. Conclusions and recommendations

This paper addresses the impact of disposition choices on the energy use and related emissions in closed-loop supply chains. EPR based policies, employed by many governments, ignores these effects as they focus on waste avoidance.

We plead for closed-loop supply chains where recovery substitutes virgin production to minimize use energy, but also avoids material use and reduces economic cost. It is shown that current EPR policy cannot work due to sunk cost and that other measures are necessary. The key of these measures is to discourage open-loop and to optimize priority sequences of remaining recovery options according a balanced energy and economical models on a case level. Energy targets combined with taxes on bad performing closed loop supply chains and subsidies on good ones prove the most effective approaches. However, not in all cases is it possible to impact disposition choices. Therefore, performance improvement policies must focus on improved DfX and collection, thereby keeping the energy perspective. This will particularly increase the fraction of returns feasible for remanufacturing and recycling and improve overall eco-eco performance of the closed-loop supply chain.

To us it appears that the relevance of the closed-loop concept in general, and energy aspects in general will only gain momentum. Some strong assumptions in the model may elicit some skepticism but can also be seen as a challenge to change behavior and the way we do things altogether. We elaborate below.

Consumers become more sensitive to the supply chain. CNW Market Research conducted a (according to some controversial) "Dust to Dust" study, tracking the energy used in creating, operating, and scrapping numerous different types of cars, even taking into account the different amounts and types of pollution caused by production in different countries (including whether factory workers are likely to commute via public transportation). The ‘surprising’ result is that based on these data, it's possible to claim that Hummers are a more energy-efficient choice than hybrids (www.treehugger.com).

Business models must accommodate the substitution of newly - and closed-loop (re) manufactured products, i.e. reuse must be invisible to the customer in terms of quality and functionality. This also requires the reverse channel to be a competitive supplier of components (closed-loop remanufacturing), materials (recycling) and energy (disposal). In fact, securing supply of materials and energy is becoming a strategic issue.

Now a fully *autarkic supply chain*, is in our view not fully realistic, but an integrated closed-loop supply chains can offer (as good as) new, green products at reduced prices due to high quality recovery.

Avoiding open-loops remains a sensitive issue as these (cascade) markets are profitable and lower social classes benefit from open-loop remanufacturing. But it does increase energy use in the user phase, and it also creates a disposal problem, often in developing countries with a less develop infrastructure for collection and recovery. So the challenge is to have a closed-loop after the open-loop, where the latter then automatically becomes life cycle extension.

Moreover, we need to find out how to include context specific parameters in a universal framework. Instead of regulation, industry and government might decide to enhance certification like ISO 14.000 or another instrument to green supply chains. Energy labels are already in place for energy use of the *product* itself. Why not extend energy labels with supply chain energy use?

In the future, rising cost of energy (and materials) as well as environmental issues will foster the substitution effect and hence policies based on this principle will become more self evident than they are today. Our generic model, possibly extended, can serve as a framework for supporting researches on the above topics in different industries.

References

Bloemhof-Ruwaard, J.B., L.N. Van Wassenhove, H.L. Gabel, and P.M. Weaver (1996), “Environmental Life Cycle Optimization model for the European pulp and paper industry” *Omega, an international journal of management science*, 24(6), pp.615-629.

Braungart, M., W. McDonough and A. Bollinger (2007), “Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design”, Journal of Cleaner Production, 15, pp. 1337-1348

Chung, S.W. and F. Yoshida (2006), “Transition from the producer deposit refund system to the Extended Producer Responsibility regime in Korea: current state and policy challenges regarding mainly consumer appliances”, working paper, Graduate School of Economics and Business Administration, Hokkaido University, Sapporo, Japan

European Parliament and The Council (2003). “Directive 2002/96/EC of 27 January 2003 on waste electrical and electronic equipment (WEEE)”, *Official Journal of the European Union*, 13.2.2003, L 37/24-38.

Fleischmann, M, H. Krikke, R. Dekker, and S.D. Flapper (2000), "A Characterization of Logistics Networks for Product Recovery", *Omega, the international journal of Management Science*, 28-6 , pp. 653 -666

Gungor A, and S.M. Gupta (1999), "Issues in environmentally conscious manufacturing and product recovery: a survey." *Computers & Industrial Engineering* 36, pp. 811-853.

Guintini, R. and K. Gaudette (2003). "Remanufacturing: The next great opportunity for boosting US productivity", *Business Horizons*, Nov-Dec. 2003.

Guide, D. and L.N. Van Wassenhove (2001). "Managing product returns for remanufacturing", *Production and Operations Management*, 10(2), pp.142-154

Hammond, D. and P. Beullens (2007). "Closed-loop supply chain network equilibrium under legislation", *European journal of operational research*, 183(2), pp.895-908

Hauser, W. and Lund, R.T. (2003). "The Remanufacturing Industry: Anatomy of a Giant. A view of Remanufacturing in America based on a comprehensive Survey Across the Industry". *Technical paper*, Department of Manufacturing Engineering, Boston University, Massachusetts.

Huppes, G. and M. Ishikawa (2005), "Eco-efficiency and Its Terminology", *Journal of Industrial Ecology*, 9-4, pp. 43-46

Kerr, W. and C. Ryan (2001), "Eco-efficiency gains from remanufacturing: a case study of photocopier remanufacturing at Fuji Xerox Australia", Journal of Cleaner Production, 9, pp. 75-81

Krikke, H.R., J.B. Bloemhof-Ruwaard J, and L.N.Van Wassenhove (2003). "Concurrent product and closed-loop supply chain design with an application to refrigerators" , *International Journal of Production Research*, 41(16), pp. 3689-3719.

Lambert A.J.D. "" Disassembly sequencing: A survey", *International Journal of Production Research 2003*; 41(16), pp. 3721-3759.

Le Blanc, H.M., "Closed-loop supply chains management: designing reverse supply chains for end-of-life vehicles", Ph.D thesis, CentER, nr.160, Tilburg University, 2006

Michelsen, O., A. Magerholm Fet, and A. Dahlsrud (2007), “Eco-efficiency in extended supply chains: a case study of furniture production”, *Journal of Environmental Management,* 79, pp. 290-297.

Nnorom, I.C. and O. Osibanjo (2008), “Overview of e-waste management practices and legislations , and their poor applications in the developing countries”, *Resources, conservation and recycling,* 52, pp. 843-858

Ogushi, Y. and M. Kandlihar (2007), “Assessing Extended Producer Responsibility laws in Japan”, Environmental Science and Technology, 41-13, pp. 4502-4508

Thierry, M., M. Salomon, J. van Nunen and L. van Wassenhove (1995). “Strategic issues in product recovery management”, *California Management Review* 37 (2), pp.114-135.

OECD (2001), Proceedings of OECS seminar on extended producer responsibility, 13-14 December 2001, Paris, France.

Van Wassenhove, L.N., Chan P., and Narayan P (2004). “The WEEE challenge.”, *INSEAD Case Study,* Fontainebleau, France. ©2004, retrieved from www.insead.edu, last visited June 2007.

Quariguasi Frota Neto, J., J.M. Bloemhof-Ruwaard, J.A.E.E. van Nunen and H.G.W.M. van Heck (2008a), Designing and evaluating sustainable logistic networks, *International Journal of Production Economics,* 111-2, pp.

Quariguasi Frota Neto, J., G. Walther, J. Bloemhof, J.A.E.E. van Nunen, Th. Spengler (2008b), “A methodology for assessing eco-efficiency in logistics networks”, *European Journal of Operational Research, 191 (3-16),* pp.

Srivastava, S.K. (2007), “Green supply chain management: a state-of-the-art review”, *International Journal of Management Reviews,* 9(1), pp.53-80

Walter, G. and Th. Spengler (2005). “Impact of the WEEE-directive on Reverse Logistics in Germany”, *International Journal of Physical Distribution and Logistics Management*, 35(5), pp. 337-361

Zipkin, P.H. (2000). “Foundations of inventory management”, McGraw-Hill, Boston. ISBN 9780256113792

Zuidwijk, R. and H. Krikke (2008). "Strategic response to the WEEE-directive: Product eco-design or new recovery processes?" *European Journal of Operational Research, 191 (3-16), pp.1206-1222*

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Appendix I. Notation and interpretation

Functions and parameters :

$s(t)$	Sales rate (kg per time unit).
$g(t,x)$	Fraction of sales at time x that is returned at time t.
$\mu(t)$	Fraction of returns appropriate for material recycling.
$\kappa^o(t), \kappa^c(t)$	Fraction of returns appropriate for open, closed-loop remanufacturing, both marketwise and in terms of return quality
p	Per kg price of new or remanufactured (closed-loop) item.
h_r	Per kg holding cost rate of returned items (euro per kg time unit)
h_n	Per kg holding cost rate of new/remanufactured items (euro per kg time unit)
c_q^c, c_q^o	Per kg closed-loop, open-loop remanufacturing costs (euro per kg)
c_n	Per kg new manufacturing costs (euro per kg)
c_m	Per kg scrap costs (euro per kg)
ρ_m	Per kg net scrap revenues (euro per kg)
ρ_q^o	Per kg net remanufacturing revenues: open-loop (euro per kg)
ε_m	Per kg net scrap energy consumption (kW per kg)
ε_n	Per kg new manufacturing energy consumption (kW per kg)
ε_q^c	Per kg remanufacturing energy consumption: closed-loop (kW per kg)
ε_q^o	Per kg net remanufacturing energy consumption: open-loop (kW per kg)
ε_w	Per kg waste incineration energy production (kW per kg)
T	Recovery target WEEE

Derived expressions:

$B(t)$	Size of installed base (kg)
$I(t)$	Size of returns inventory (kg)
$J(t)$	Size of (re)manufactured inventory (kg)

$K(t)$	Excess amount of recovered materials relative to WEEE target (kg)
$r(t)$	Return rate (kg per time unit)

Decisions variables:

$m(t)$	Amount of products forwarded to scrap (in kg per time unit)
$q^c(t), q^o(t)$	Amount of products forwarded to remanufacturing (in kg per time unit)
$w(t)$	Amount of products waste disposed of (in kg per time unit)
$n(t)$	New product production rate (kg per time unit)

Objective functions:

$\rho(t)$	Revenue rate (euro per time unit)
$\varepsilon(t)$	Energy consumption rate (kW per time unit)

Figure 1: dynamical system

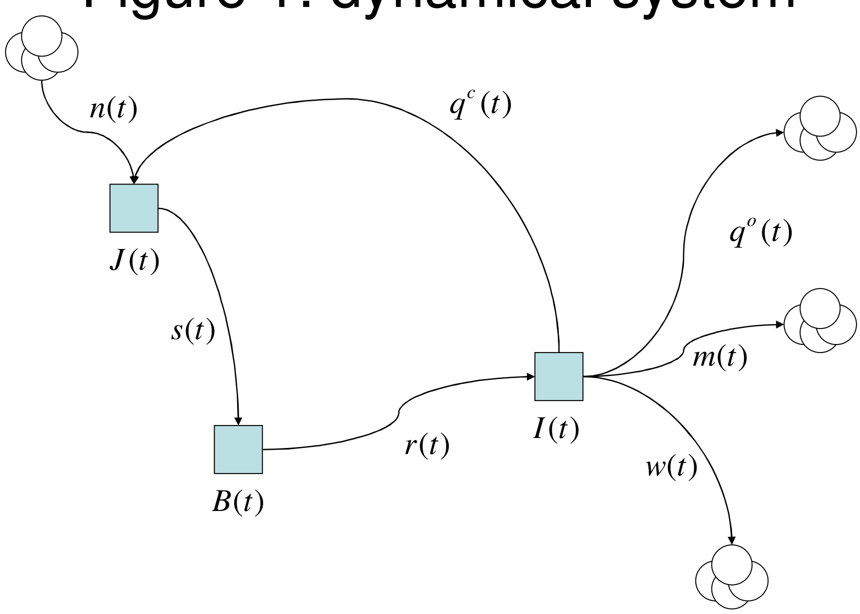

Table 3: Objective functions coefficients

Objective functions coefficients	$\overline{q}^c(t)$	$\overline{q}^o(t)$	$\overline{m}(t)$
$\overline{\rho}(t)$	$c_n - c_q^c + c_w$ 1	$\rho_q^o - c_q^o + c_w$ 2	$\rho_m - c_m + c_w$ 3
$-\overline{\varepsilon}(t)$	4 $\varepsilon_n - \varepsilon_q^c - \varepsilon_w$	5 $-\varepsilon_q^o - \varepsilon_w$	6 $-\varepsilon_m - \varepsilon_w$

Table 4: Recovery options per case

cases	TV	Industrial fridge	Copier/ CRT monitor	Spares
$\overline{q}^c$		√		√
$\overline{q}^o$		√	√	
$\overline{m}$	√	√	√	√
$\overline{w}$	√	√	√	√

Figure 2a: Policy measures

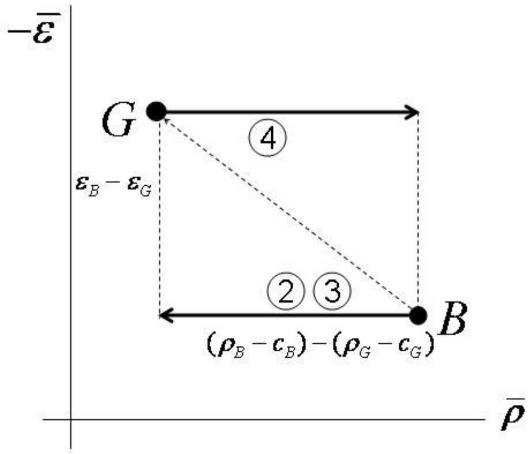

Figure 2b: Policy measures

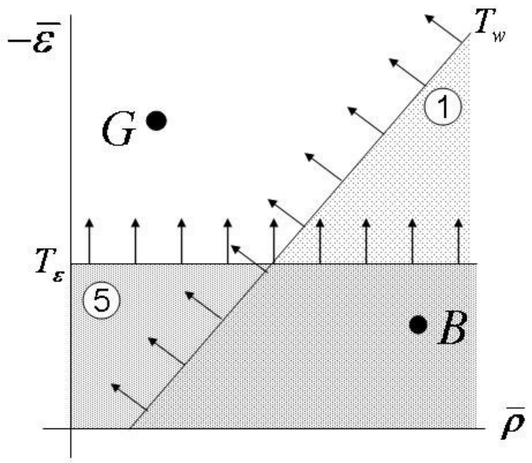

Figure 2c: Policy measures

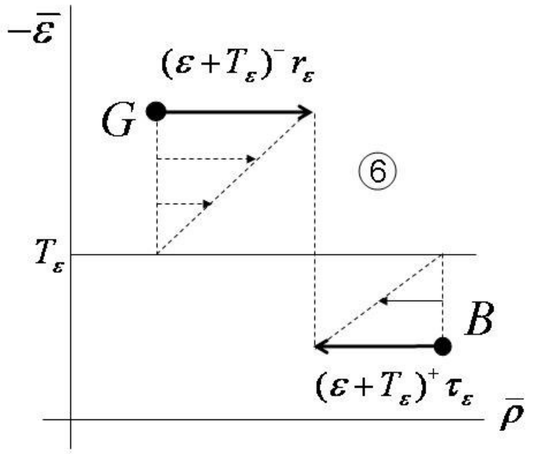

Table 5: TV case

Objective functions coefficients	$\bar{q}^c(t)$	$\bar{q}^o(t)$	$\bar{m}(t)$
$\bar{\rho}(t)$	NA ①	NA ②	0.1 ③
$-\bar{\varepsilon}(t)$ ④	NA ⑤	NA ⑥	6
Preference order	$\bar{\rho}(t)$: $\bar{m} \succ \bar{w}$ $-\bar{\varepsilon}(t)$: $\bar{m} \succ \bar{w}$		

Figure 3: TV case

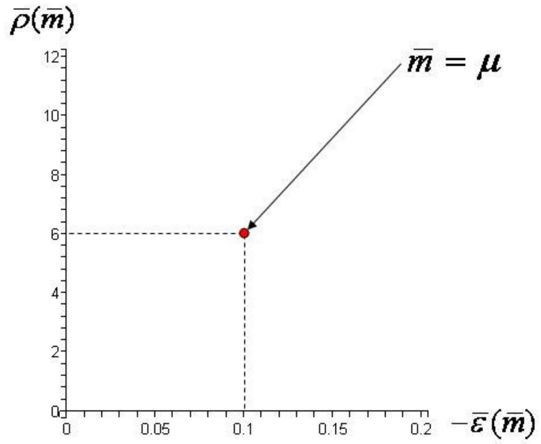

Table 6: CRT monitor case

Objective functions coefficients	$\bar{q}^c(t)$	$\bar{q}^o(t)$	$\bar{m}(t)$
$\bar{\rho}(t)$	NA 1	13 2	-0.13 3
$-\bar{\varepsilon}(t)$ 4	NA 5	-17 6	6
Preference order	$\bar{\rho}(t)$: $\bar{q}^o \succ \bar{w} \succ \bar{m}$ $-\bar{\varepsilon}(t)$: $\bar{m} \succ \bar{w} \succ \bar{q}^o$		

Figure 4: CRT monitor case

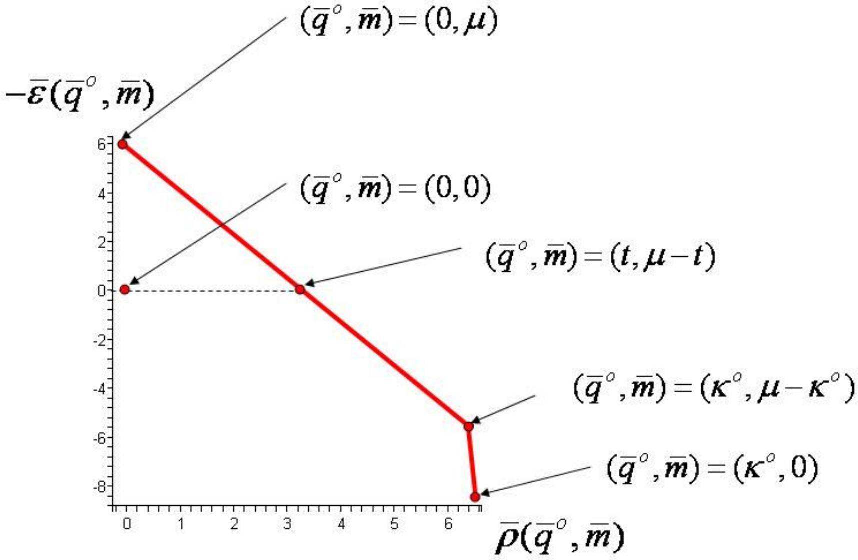

Table 7: Copier case

Objective functions coefficients	$\bar{q}^c(t)$	$\bar{q}^o(t)$	$\bar{m}(t)$
$\bar{\rho}(t)$	NA 1	6.0 2	0.25 3
$-\bar{\varepsilon}(t)$ 4	NA 5	-4 6	13
Preference order	$\bar{\rho}(t)$: $\bar{q}^o \succ \bar{m} \succ \bar{w}$ $-\bar{\varepsilon}(t)$: $\bar{m} \succ \bar{w} \succ \bar{q}^o$		

Figure 5: Copier case

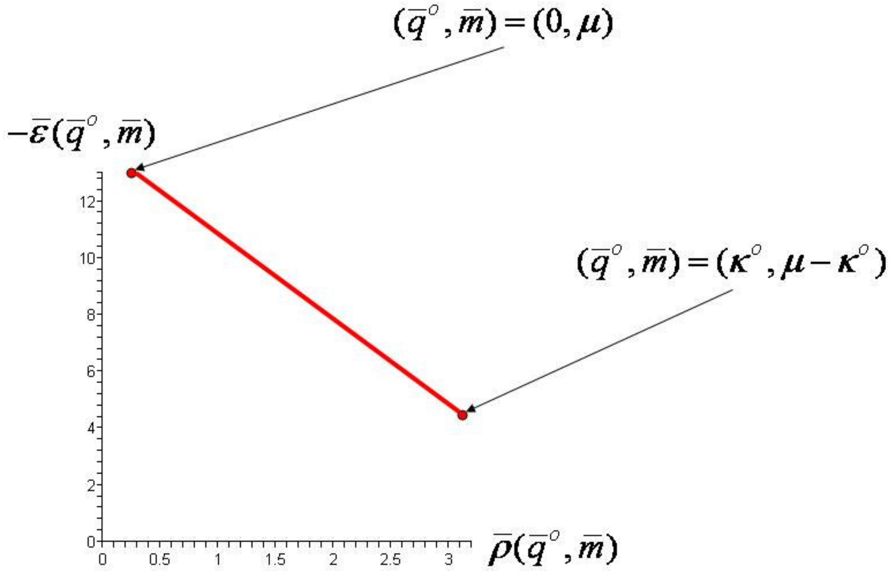

Table 8: Spare parts case

Objective functions coefficients	$\bar{q}^{c}(t)$	$\bar{q}^{o}(t)$	$\bar{m}(t)$
$\bar{\rho}(t)$	0.2 1	NA 2	0.1 3
$-\bar{\varepsilon}(t)$ 4	1 5	NA 6	0
Preference order	$\bar{\rho}(t)$: $q^{c} \succ \bar{m} \succ \bar{w}$ $-\bar{\varepsilon}(t)$: $q^{c} \succ \bar{m} \succ \bar{w}$		

Figure 6: Spare parts case

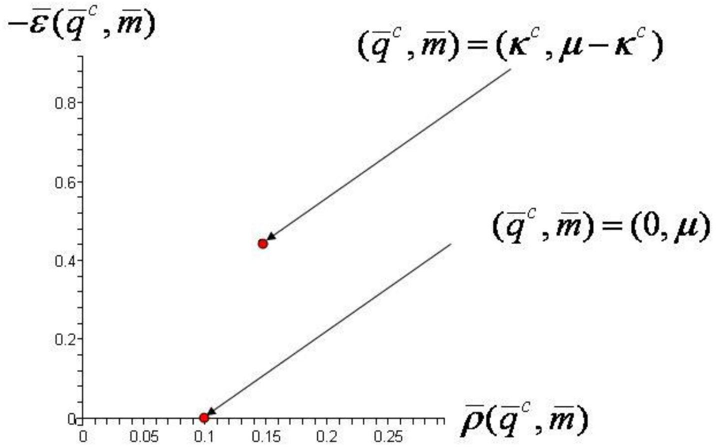

Table 9: Industrial Fridge case

Objective functions coefficients	$\bar{q}^c(t)$	$\bar{q}^o(t)$	$\bar{m}(t)$
$\bar{\rho}(t)$	0.2 ①	0.4 ②	0.25 ③
$-\bar{\varepsilon}(t)$	④ 53	⑤ 3	⑥ 29
Preference order	$\bar{\rho}(t)$: $\bar{q}^o \succ \bar{m} \succ \bar{q}^c \succ \bar{w}$ $-\bar{\varepsilon}(t)$: $\bar{q}^c \succ \bar{m} \succ \bar{q}^o \succ \bar{w}$		

Figure 7: Industrial Fridge case

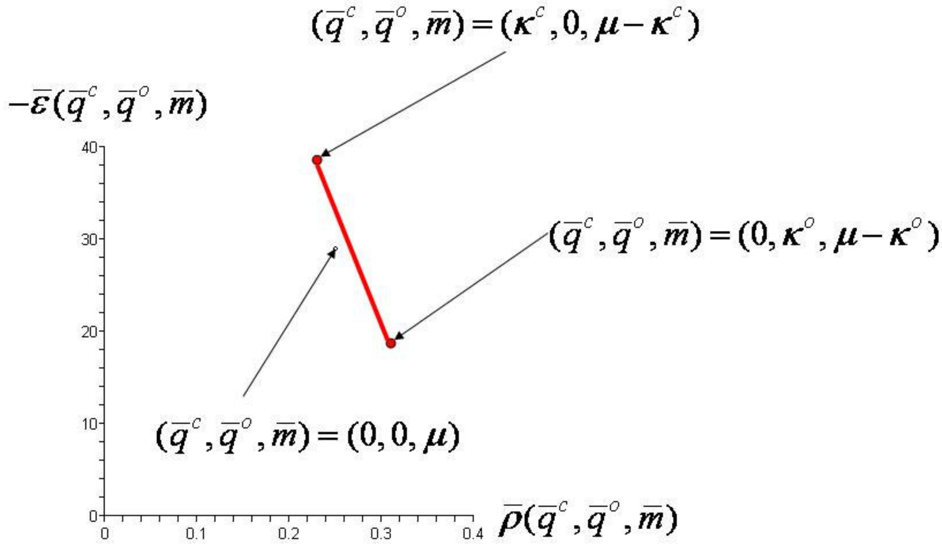

Table 10: Policy Measures in cases

Policy / Case	G	B	Target on G	Energy tax	Tax on B / Subsidy on G	Energy target	Target based energy tax
TV	Not Applicable						
CRT monitor	M	Q^o	Applicable	0.30	7	[-17,6]	
Copier	M	Q^o	NA	0.34	5.75	[-4,13]	
Spare parts	Not Applicable						
Industrial fridge	Q^c	Q^o	NA	0.004	0.2	[3,53]	